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Laboratory Observations of Plume Deformations in Neutral Flow over a Three-Dimensional Hill

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LABORATORY OBSERVATIONS OF PLUME DEFORMATIONS IN NEUTRAL FLOW OVER A THREE-DIMENSIONAL HILL

by

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16. ABSTRACT

A series of wind-tunnel measurements was made in a simulated atmospheric boundary layer of plume characteristics in flat terrain and over a three-dimensional hill. Effluent was released at a number of elevations, upwind distances, and positions laterally offset from the centerplane defined by the wind direction and the center of the hill. Sufficient concentration measurements were made to enable the construction of plume cross sections at the downwind position of the hill center and, in a few cases, at the upwind base of the hill. These data were analyzed to provide the desired information on horizontal and vertical plume deflections and deformations over the hill.

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LABORATORY OBSERVATIONS OF PLUME DEFORMATIONS IN NEUTRAL FLOW OVER A THREE-DIMENSIONAL HILL

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1. INTRODUCTION

Qualitative features of the transport and dispersion of plumes over hills are generally well-understood. There is, however, a dearth of quantitative information that may be used for definitive testing of mathematical models. Most air pollution experts would agree that plumes are stretched and deformed over hills and that plume centerlines approach hill surfaces more closely than would be so over flat terrain, but estimates of the amounts of the deformations and approach distances and, especially, the ultimate effects of these changes on surface concentrations would vary widely. Similarly, most experts would agree that turbulence is increased close to a hill surface, but the amount of the increase and its effects on transporting plume material to the hill surface would be argued vehemently. The measurements to be presented herein were made in an attempt to provide detailed plume-structure data in a simulated neutral atmospheric boundary layer flow over a realistic hill shape. These data are directly useful as an aid to physical understanding; they are particularly useful as a relatively complete data set for the development, refinement and evaluation of complex terrain dispersion models. For additional information on terrain effects on plume dispersion in neutral flows, see Castro and Snyder (1982) for sources downwind of hills, Snyder and Britter (1986) for sources upwind of hills, and references contained therein.

A series of measurements was made of plume characteristics in flat terrain and over a three-dimensional hill. Effluent was released at a number of elevations, upwind distances, and positions laterally offset from the centerplane defined by the wind direction and the center of the hill. Sufficient concentration measurements were made to enable the construction of plume cross sections at the downwind position of the hill center and, in a few cases, at the upwind base of the hill. These data are analyzed to provide the desired information on horizontal and vertical plume deflections and deformations over the hill.

Measurements over both smooth- and rough-surfaced hills provide information on the effectiveness of the "hill surface boundary layer" in mixing of material from an elevated plume onto the hill surface. Our postulate here is that roughness on the hill would maximize the effects of a rapid-mixing layer near the hill surface, thus mixing material from an elevated plume to the surface, whereas a smooth surface would minimize the effects of this mixing layer.

2. METHODS

A simulated neutral atmospheric boundary layer of 1m nominal depth was set up in the Meteorological Wind Tunnel of the EPA Fluid Modeling Facility (Snyder, 1979). The surface roughness was fine Sanspray (3mm dia. gravel). Two axisymmetric hill models were constructed. The shape was an idealization of Cinder Cone Butte (CCB) in Idaho. One of the models had a smooth surface (CCBS), the other, rough (CCBR), with the same roughness as the flat terrain surrounding the hills. A rough, flat-terrain section was also constructed to be inserted in place of the hills, so that the plume structure could be measured in the absence of the hills.

The hills were 155mm in height. Their shape is described by $f(r)=[(h+c)/[1+(r/L)^4]]-c$, with h=155mm, L=388mm, and c=10mm for $r<775$mm and $f(r)=0$ for $r>775$mm. The maximum slope was 0.45 or 24°.

The source was a porous ball of 10mm dia. Ethane (neutrally buoyant) was used as the tracer gas. Nondimensional tracer-gas concentrations are reported as $\chi = CU_\infty h^2/Q$, where C is the volume concentration, U_∞ is the freestream wind speed (4m/s), h is the hill height, and Q is the flow rate of ethane from the source (2980cc/min). The results will be presented in nondimensional form, scaling lengths, for example, by the hill height. Strictly speaking, the model scale ratio may be considered as approximately 1:1000 based primarily upon the boundary-layer depth. Since the ratio of the boundary-layer depth to hill height is large, however, we do not expect the results to be very dependent upon this ratio. Thus, for practical purposes, the results may be more generally applied to a much wider range of hill sizes.

3. RESULTS

Sufficient measurements were made of the flow structure and dispersive characteristics of the boundary layer over the flat terrain to establish that the setup produced a reasonable simulation of the neutral atmospheric boundary layer (Lawson and Snyder, 1986). This boundary layer was approxi-

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† On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

TABLE I. SUMMARY OF SOURCE/HILL CONFIGURATIONS AND PLUME STATISTICS

Case No.	Hill	Source Coordinates			Downwind Distance	Lateral Distributions					Vertical Dimensions	
		H_s/h	x_s/h	y_s/h	x/h	z/h	y/h	σ_y/h	Skewness	Kurtosis	(1) Σ_z^+/h	(2) Σ_z^-/h
1	FLAT	0	- 6	0	0	0	0	.43	- .032	2.84	.50	0
2	FLAT	0	-16	0	-6	0	-.01	.64	- .018	2.74	.81	0
3	FLAT	0	-16	0	0	0	-.01	.85	- .043	2.70	1.16	0
4	ACCBR	0	- 6	0	0	0	.01	.83	- .021	2.68	.48	0
5	ACCBR	0	-16	0	-6	0	-.01	.68	.003	2.78	.87	0
6	ACCBR	0	-16	0	0	0	-.01	1.35	- .019	2.33	.84	0
7	ACCBR	0	- 6	-1.29	0	0	-2.24	.59	.573	3.18	.56	0
8	FLAT	0.52	- 6	0	0	0	-.01	.41	- .085	2.95	.71	.39
9	ACCBR	0.52	- 6	0	0	0	.01	.57	- .049	2.61	.56	.17
10	ACCBR	0.52	- 6	-1.29	0	0	-1.66	.51	.304	2.78	.70	.26
11	ACCBS	0.52	- 6	0	0	0	-.03	.59	- .024	2.51	.56	.17
12	FLAT	1.23	- 6	0	0	1	-.03	.44	- .060	2.95	.77	.66
13	ACCBR	1.23	- 6	0	0	0.52	-.01	.49	- .039	2.62	.74	.45

(1) Σ_z^+/h is the distance upwards from the location of the maximum concentration to the point where the concentration is 10% of the maximum.

(2) Σ_z^-/h is the distance downwards from the location of the maximum concentration to the point where the concentration is 10% of the maximum, or to the surface, whichever is less.

mately 0.8m (5h) in depth, with a roughness length of 0.1mm (approximately 10cm full scale), and a friction velocity of u_*/U_∞=0.045. Detailed measurements were also made of the mean and turbulent flow structure on the centerplane over the hill as well as terrain amplification factors for a matrix of source locations both upwind and down wind of the hill; these measurements are reported separately (Lawson and Snyder, 1986).

In all, 13 detailed plume cross sections were measured. The various hill/source configurations are summarized along with pertinent plume statistics in Table I.

One of the more dramatic examples of plume stretching by the hill is shown in Figure 1. In this case, the source was on the centerplane (y_s=0) at ground level (H_s=0), 6h upwind of the hill center (the upwind skirt of the hill extended to 5h). (Note that the center of the porous-ball source was, in fact, at H_s/h=0.03, but is referred to as a ground-level source, and reported as H_s/h=0.) Plume cross sections measured at the position of the hill center both in the presence and in the absence of the hill are shown. The hill effected a 91% increase in the lateral plume width, σ_y. The surface concentration (at the same downwind distance) was decreased by a factor of 2 but, of course, the area of coverage by large concentrations was greatly increased. Streamline contraction in the vertical certainly occurs, but, surprisingly, the net change in the vertical plume dimension was only a few percent; using the

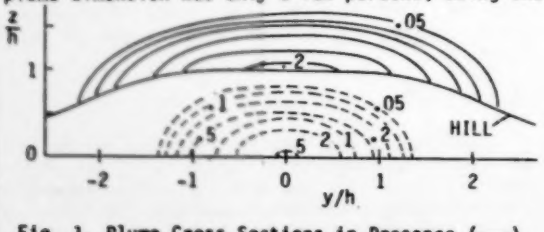

Fig. 1. Plume Cross Sections in Presence (——) and in Absence (---) of Rough Hill at x=0. H_s/h=0, x_s/h=-6, y_s/h=0.

distance from the surface to the point where the concentration is one-tenth the maximum as a measure of the vertical plume width, Σ_z, the net change was a 4% decrease. These results suggest that any streamline contraction in the vertical was compensated, at least in this case, by enhanced vertical diffusion.

For higher sources, plume deformations were less dramatic, but the effects were still quite significant. For example, for a source at the same location (x_s=-6h), but with height about half the hill height (H_s=0.52h), σ_y was increased by 40% at ground level (see Figure 2). The distance from the surface to the plume centerline (loosely defined here as the locus of maximum

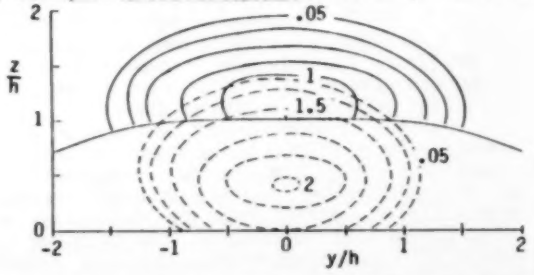

Fig. 2. Plume Cross Sections. Source at H_s/h=0.52, x_s/h=-6, y_s/h=0.

concentration) was decreased by a factor of 2, the net result being that the surface concentration was increased by a factor of 2.7! The vertical plume width was also significantly reduced (cf., Table I, Case nos. 8 and 9); in this case, the vertical contraction of streamlines clearly dominated the vertical diffusion in determining the plume shape.

For an even higher source (H_s=1.23h), only the extreme edge of the plume contacted the hill surface, but, even so, the lateral plume width was increased measurably (11%) by the presence of the hill (Figure 3). The upper portion of the plume (above the level of the maximum concentration) was clearly displaced vertically by the

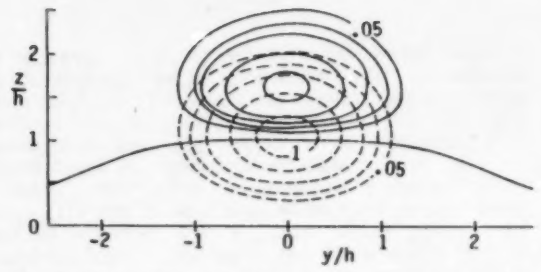

Fig. 3. Plume Cross Sections. Source at H_s/h=1.23, x_s/h=-6, y_s/h=0.

hill, but plume contraction in the vertical direction was not evident (or slight, at most; cf., Σ_z^+ in Table I, Case nos. 12 and 13). The lower portion of the plume, however, has clearly undergone significant vertical contraction (cf., Σ_z^-, Table I).

Two vertical concentration distributions measured through this plume are shown in Figure 4, where they are compared with distributions measured at comparable positions over the smooth-surfaced hill. The surface roughness clearly has a negligible effect, as the respective profiles

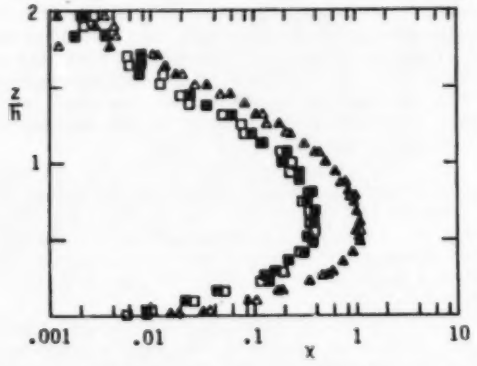

Fig. 4. Vertical Concentration Distributions over Smooth (open symbols) and Rough (filled) Hills at x=0. y/h=: △,0; □,0.65. H_s/h=1.23, x_s/h=-6, y_s/h=0.

are essentially identical, and all four profiles display extremely steep concentration gradients near the hill surfaces. These results strongly suggest that the postulate of a "hill surface boundary layer" that rapidly mixes material from an elevated plume to the surface is untenable, i.e., if such rapid mixing took place, we would expect to observe virtually zero concentration gradients near the surface. We would also expect to see substantial differences in the near-surface concentrations if the rough hill induced a much deeper and more vigorous mixing layer, e.g., if the depth of this "hill surface boundary layer" were, say, 0.1h, we would expect to see an increase in surface concentration on the rough hill as compared with the smooth hill by a factor of 3 (cf., Figure 4).

Measurements over the smooth- and rough-surfaced hills with a source height of 0.52h (Case nos. 9 and 11, Table I) also showed negligible differences, but, because near-surface concentration gradients were small (Figure 2), this test may not be used as judicially as was that for the higher stack.

Plume cross sections for a ground-level source offset from the centerline (y_s=-1.29h) are shown in Figure 5. Compared with the non-offset source, the increase in lateral plume width was less dramatic, but still quite significant (36% increase). The lateral deflection of the plume is striking; the locus of maximum concentration is now offset by 2.4h, suggesting an effective change in wind direction effected by the hill of 10°. Notice that the maximum surface concentration (at x=0) is higher (by 36%) than that for the non-offset source (Figure 1). Notice also that the surface concentration distribution is obviously skewed (Table I). For a similarly offset (y_s=-1.29h) but higher (H_s=0.52h) source (cross sections not shown), the lateral deflection of the plume was about half that of the present case, i.e., the data suggested an effective change in wind direction of 5° at ground level.

In the final set of measurements, the source was moved to a position 16h upwind of the hill center in order to obtain a larger plume at the upwind skirt of the hill. Cross sections were measured both upwind of the hill (x=-6h) and at the position of the hill center (x=0), both in the presence and in the absence of the hill. The cross sections upwind of the hill are shown in Figure 6; clearly, the influence of the hill on the plume at this position was quite small, as the cross sections in the presence and absence of the hill are practically identical. The plume widths differ by 6% and the maximum surface concentrations differ by 8%; these differences are only slightly, if at all, outside the range of repeatability of these kinds of measurements.

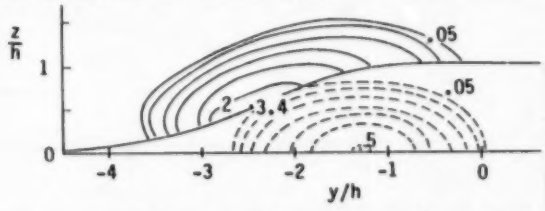

Fig. 5. Plume Cross Sections at x=0 with Offset Source. H_s/h=0, x_s/h=-6, y_s/h=-1.29.

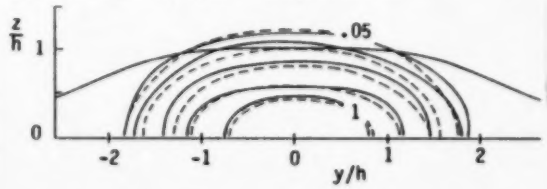

Fig. 6. Plume Cross Sections at x/h=-6. H_s/h=0, x_s/h=-16, y_s/h=0.

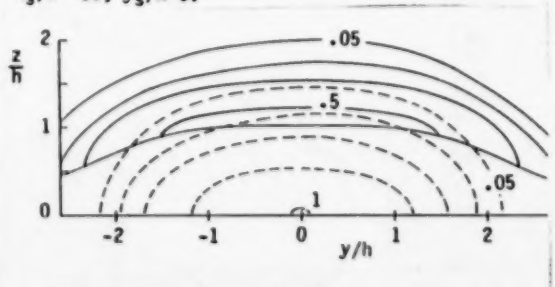

Fig. 7. Plume Cross Sections at x=0. H_s/h=0, x_s/h=-16, y_s/h=0.

Strong distortions of this plume are, however, effected by the hill in travelling from the upwind skirt to the hill center (Figure 7). The increase in lateral plume width was quite significant (57%), plume contraction in the vertical was apparent (Σ_z suffered a decrease of 30% below its value in flat terrain), and the value of the maximum surface concentration (at x=0) was decreased by 40%.

Graphs of lateral plume widths are shown in Figures 8 (x_s=-6h) and 9 (x_s=-16h). Figure 8 shows that the greatest increase in lateral plume width occurs for the lowest source, and that these distortions diminish as the source height is increased. Offsetting the source from the centerline also diminishes the lateral spread rate of the plume. Figure 9 shows that the plume deformation caused by the hill is small all the way to the upwind skirt of the hill, but very significant deformations occur over the hill itself.

4. CONCLUSIONS

1. The postulate of an "inner hill-surface boundary layer" that results in rapid mixing of elevated plume material to the hill surface is untenable. The extremely steep concentration gradients that remain near the hill surface even when the hill is roughened simply do not support this postulate as a viable physical mechanism.

2. Strong plume deformations in the lateral direction are effected by the hill. For a ground-level source located 6h upstream of the hill center, σ_y/σ_y°=1.91, i.e., a 91% increase in the lateral plume width was observed. These deformations decrease as the source height increases, but even for a source height of 1.23h (also 6h upstream), σ_y/σ_y°=1.11. For a ground-level source located 16h upstream, the distortions were smaller, but still very significant; σ_y/σ_y°=1.58. These magnitudes of deformation far exceed those typically calculated using potential flow theory.

3. Plume deformations in the vertical direction are also effected by the hill, but because the effects of streamline contractions are opposite to those of enhanced diffusion, the net changes to be observed in the vertical dimensions of the plume are not immediately obvious. The measurements suggest that for thin plumes close to the surface, the two mechanisms effecting changes in the vertical plume dimensions are of approximately equal strength. Thus, we may expect, in such cases, vertical plume widths will remain approximately constant. On the other hand, for elevated plumes or deep plumes that may even contact the hill surface, the dominant mechanism is the streamline contraction, so that we may expect vertical plume widths to be decreased as the plumes travel over the hills.

4. For laterally offset sources, the loci of maximum surface concentration are deflected widely around the sides of the hill. The present measurements suggest maximum effective changes in wind direction of around 10° for a ground-level source, decreasing to about 5° for a half-hill-height source.

5. A plume released far upstream of the hill showed little or no change in shape (caused by the hill) at the upwind base of the hill, suggesting that all plume deformation takes place between the upwind base and top of the hill.

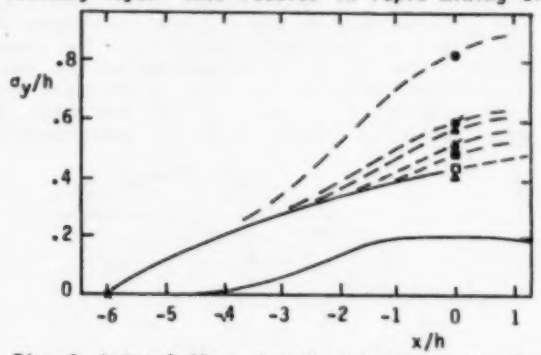

Fig. 8. Lateral Plume Growth with Source at -6h. Open symbols: flat terrain; closed: rough hill; flagged: offset source. Hs/h=: ○, 0; △, 0.52; □, 1.23.

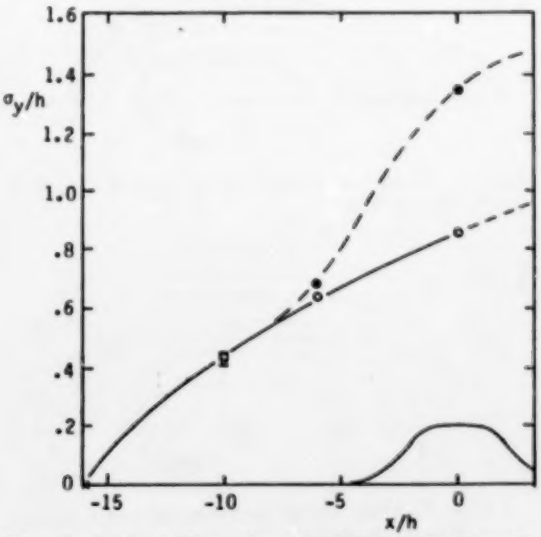

Fig. 9. Lateral Plume Growth with Source at -16h. Symbols as in Figure 8.

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